IN THE SPECIFICATION:

Page 33, please amend paragraph 176 as follows:

[00176] As can be seen in this graph, errors in focus and dose can lead to two opposite effects, which can trigger a failure mechanism for the lithographic process. The first effect is characterized by a CD increase outside the range (corresponding to "smiling curves") of acceptable CDs while the second effect is characterized by a CD decrease outside this range (corresponding to "frowning curves").

Page 38, please amend paragraph 202 as follows:

[00202] The lithographic problem studied was a pattern of 90 nm holes in a 360 nm pitch (See FIG. 26c). FIG. 26a represents a contour map of the metric-responses obtained with resist calculation. In that case, the metric calculates and compares the critical dimension of the pattern obtained at best focus and defocus (i.e. CD(best focus + 0.2μm) – CD(best focus)). FIG. 26b is an example of a contour map, which is obtained with aerial image simulation. In this example, the metric compares the intensity threshold at best focus and the intensity threshold for a 0.2 μm defocus (i.e. thresh(best focus) – thresh(best focus + 0.2 μm). In this embodiment, it should be noted that a variation of the threshold intensity in an aerial image simulation is equivalent to a CD variation.

Page 38, please amend paragraph 204 as follows:

[00204] Referring now in more detail to FIG. 26a, the regions of the illuminator producing an augmentation of the CD are concentrated in the extreme bottom left of the quadrant (i.e. CD(best focus + 0.2 μm defocus) is greater than CD(best focus)). They reflect a CD augmentation of around 25-50nm. This corresponds in a Bossung plot to a "smiling" curve. By contrast, the areas of the illuminator creating a diminution of the CD are located in the center of the map. In that case, the curves in the Bossung plot will "frown" severely and holes will be closed (CD=0) when out of focus. Areas where curves in the Bossung plot will frown less severely are located in the upper right portion of the contour maps.

Page 38, please amend paragraph 206 as follows:

[00206] These contour maps may be reduced in one embodiment of the invention to contour maps representing opposite isofocal behaviors, as shown in FIGS. 27a-b. FIG. 27a

represents a contour map of the metric-responses obtained with FIG. 26a (i.e. CD(best focus + 0.2μm) – CD(best focus)). FIG. 27b shows a contour map obtained with results of FIG. 26b (i.e. thresh(best focus) – thresh(best focus + 0.2 μm).

Page 39, please amend paragraph 210 as follows:

[00210] The balancing of the regions may be done in an embodiment of the invention by selecting some source points in the positive regions and in the negative regions, as shown in FIG. 28. In FIG. 28, circle AC that delineates a 0.25 sigma on axis illumination captures source points that produce a CD augmentation and source points that produce a CD reduction. Practically, selection of these source points should take into account the aptitude of these source points to print the target CD. In other words, in this embodiment of the invention, a weight may be attributed to each source point. In the case of an aerial image simulation, the weight of a source point will depend on the intensity of the aerial image obtained from this source point. In the case of a full resist calculation, the weight of a source point will be inversely proportional to the dose required to print the target CD (i.e. CD to size) at best focus. As a result, if the required dose is low for this source point, then that point may potentially counterbalance a relatively larger area in the region of opposite sign. Naturally, if the source points have substantially the same weight, the balancing of the regions is done by selecting an equal number of source points in the positive regions and in the negative region. In FIG. 28, this results in selecting a 0.25-σ illumination arrangement (i.e. the arrangement that defines an aperture corresponding to the arc shown in FIG. 28). In so doing, the lithographic process is rendered substantially isofocal over the range of defocus studied. At σ=0.25, the lithographic process is approximately isofocal. The depth of focus is good but the dose latitude is low.

Page 40, please amend paragraph 214 as follows:

[00214] FIGS. 30a-b illustrate contour maps obtained with a full resist calculation. In the first graph, the response studied is the maximum exposure latitude. In the second graph, the dose-to-size E1:1 response is analyzed. As can be seen in these graphs, different areas of the illuminators give different values for these responses and will contribute to an optimization of the illumination conditions. For example, the areas of the illuminator that will enhance the exposure latitude are located in the upper right portion of the quadrant. These areas define a quadrupole off-axis illumination including poles arranged at +/- 45° relative to the horizontal axis of the illuminator (this illumination may be referred to as

"quasar" type illumination). Similarly, useful areas that lead to a favorably low E1:1 are also situated in the upper right portion in the contour map (strong aerial image). In contrast, areas located proximate the lower left portion of the map (corresponding to a low sigma on-axis illumination) provide poor exposure latitude and require high doses to print (weak aerial image).

Page 41, please amend paragraph 215 as follows:

[00215] It is therefore expected that the best illumination conditions to print the 90 nm holes in a 360 nm pitch will be provided by an illumination arrangement as shown in FIG. 31. This figure indicates the profile of the projection beam in the pupil plane of the illuminator. The sigma range along the X-axis and Y-axis of FIG. 31 is from -1 to +1. This arrangement combines a on-axis illumination and off-axis quasar illumination. Specifically, the arrangement includes a 0.1 on axis sigma illumination and a quadrupole illumination having four off-axis poles arranged at +/- 45° relative to the horizontal axis of the illuminator (this illumination may be referred to as quasar type illumination). The poles have a 5° opening angle, a 0.88 inner radius and a 0.92 outer radius (this illumination may be referred to as σ(0.1 conv) + (0.92/0.88Q5°). Simulated results in terms of depth of focus and exposure latitude obtained with the illumination arrangement shown in FIG. 31 are provided respectively in FIGS. 32 and 33. As can be seen in these graphs, there is almost no variation of the CD and the exposure latitude through defocus.

Page 41, please amend paragraph 216 as follows:

[00216] FIG. 34 compares variation of the exposure latitude with defocus for a process optimized with (1) standard calculation (in that case a full resist calculation) which maximizes depth of focus at a fixed dose latitude (with off-axis quadrupole illumination having four poles arranged at +/- 45° relative to the horizontal axis that each have a 30° opening angle, a 0.7 inner radius and a 0.95 outer radius – 0.95/0.70Q30°), (2) isofocal compensation based on a simple illuminator design (having a 0.25 σ on-axis illumination) or (3) isofocal compensation using a complex illuminator and targeting maximum dose latitude (the illuminator combines a 0.1 σ on-axis illumination and a quadrupole off-axis illumination having four poles, arranged at +/- 45° relative to the horizontal axis, that each have a 5° opening angle, a 0.88 inner radius and a 0.92 outer radius – 0.92/0.88Q5° + 0.1 conv). Results in terms of maximum exposure latitude (max EL), maximum depth of focus (max

DOF), depth of focus at 10% of exposure latitude (DOF@10%EL) and depth of focus at 5% of exposure latitude (DOF@5%EL) are shown in table (a)

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optimization method	illumination	max EL	max DOF	DOF @ 10% EL	DOF @ 5% EL
standard	0.95/0.70Q30°	18%	0.3	0.18	0.24
simple isofocal compensation	0.25 conv	8%	>0.55	0	0.29
high EL isofocal compensation	0.92/0.88Q5°+0.1conv	16%	>0.65	0.57	0.63

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Table (a)

This figure shows that isofocal compensation substantially increases the DOF. This figure also shows that the exposure latitude can be greatly increased while maintaining high DOF by combining appropriate parts of the illuminator. Therefore, large improvement in the process window may be possible with appropriate use of the illuminator to compensate for isofocal curvature. Note that the same enhancement could be obtained by analyzing aerial image calculations including information on the NILS at best focus. Because NILS is proportional to exposure latitude, such an analysis would also lead to a combination of on-axis and off-axis illumination to give isofocal performance with high dose latitude.

Page 42, please amend paragraph 219 as follows:

[00219] Simulated results in terms of depth of focus measured at 8% of the exposure latitude (DOF@8%EL) are illustrated in FIG. 36a for the types of illumination arrangement predicted with the method of the present invention. This graph shows the variation of DOF@8%EL as a function of the pitch. For reference, FIGS. 36b and 36c illustrate the source shape with two types of arrangement (in terms of NA and quasar illumination) at the pupil plane of the illuminator. The sigma range along the X-axis and Y-axis of FIGS. 36b-c is from -1 to +1. FIG. 36b shows a 0.90/0.40+0.4σ illumination arrangement that includes a 0.4 σ on-axis illumination and a quadrupole illumination including four off-axis poles that are arranged at +/- 45° relative to the horizontal axis of the illuminator. Each off-axis pole has a 0.4 inner radius and a 0.9 outer radius. FIG. 36c shows a 0.97/0.40+0.4σ illumination arrangement that includes a 0.4 σ on-axis illumination and a quadrupole illumination including four off-axis poles that are arranged at +/- 45° relative to the horizontal axis of the illuminator. Each off-axis pole has a 0.4 inner radius and a 0.97 outer radius.

Page 44, please amend paragraph 225 as follows:

[00225] An example of CD variations generated by lens aberration is shown in FIG. 38a. This figure illustrates simulated CD variations (in arbitrary units) of a double line

structure and more particularly, the difference in width between the left and right line (of this double line structure) as a function of lens aberration. This structure was selected in this trial for its good sensitivity to lens aberrations. For reference, the double line structure is depicted in FIG. 38b. As can be seen in this figure, this structure includes two lines (identified as "L" in FIG. 38b) having a width of 50nm. The pitch of the lines is 230nm and the pair repeats at a larger pitch. A transparent 180° phase shift window PSW is also placed between the lines (See FIG. 38b).

Page 44, please amend paragraph 226 as follows:

[00226] In this trial, simulations of CD variations are performed for three similar lenses with a lithographic projection apparatus having a numerical aperture of 0.75NA, an illumination condition of 0.25σ and a radiation of 157nm (TI 180/230/800). For each lens, the RMS (Root Mean Square) values of an aberration set, which correspond to aberrations on several points of the lens field, are known and have been extracted using conventional measurement techniques (by interferometry, for example). Each RMS value, each corresponding to an aberration measured at a specific point in the field, represents the quadratic sum of the (Zernike) coefficients of the Zernike polynomial, which is used to model the wavefront aberration at this specific point in the lens. More specifically, this RMS value represents the departure of the wavefront of the propagating wave from sphericity. It should be noted that, in this trial and in the embodiment of the method illustrated in FIG. 37, the aberrations are considered together as an overall wavefront error rather than as specific aberrations. In other words, each RMS aberration value may represent different types of aberrations (like the Seidel aberrations, which include coma, astigmatism, field curvature, distortion or spherical aberrations).

Page 45, please amend paragraph 229 as follows:

[00229] In order to validate the choice of the illumination arrangement (i.e. a small sigma and wide quasar illumination, see FIG. 41), a trial similar to the one illustrated in FIG. 38a is conducted. Fig. 41 shows an illuminator comparison for the double line structure. The sigma range along the X-axis and Y-axis of FIG. 41(a)-(c) is from -1 to +1. In FIG. 41, the illuminator (a) corresponds to a 0.25 σ on-axis illumination, the illuminator (b) corresponds to a 0.15 σ on-axis illumination, and the illuminator (c) corresponds to an arrangement that combines a 0.25 σ on-axis illumination and an off-axis illumination having small off-axis poles that are arranged on the horizontal and vertical axis of the illuminator (this illumination

may be referred to as "cquad type illumination"). Results of this trial are shown in FIG. 40. As can be seen in this figure, it is indicated that the alternate settings have higher sensitivity aberrations and that an illumination with σ=0.25 remains favorable to limit CD variation of the double line structure. These results clearly show that it is desirable to take into account the lens aberrations to optimize the conditions of illumination.

Page 48, please amend paragraph 239 as follows:

[00239] Referring to FIG. 43, this figure shows the variations of DOF@8%EL as a function of source point location. This contour map is obtained using embodiments of the invention illustrated, for example, in FIGS. 13 or 24. The illumination optimization is done with a 0.75 numerical aperture. As can be seen in this graph, an illumination arrangement providing a tight quasar illumination notably increases the depth of focus of the lithographic process. Specifically, the optimized illumination arrangement (0.80/0.55Q30°) includes a quadrupole off-axis illumination including off-axis poles arranged at about +/- 45° relative to the horizontal axis of the illuminator. Each pole has a 30° opening angle, a 0.55 inner radius and a 0.8 outer radius.

Page 48, please amend paragraph 240 as follows:

[00240] Results in terms of CD variation due to aberrations (aberration sensitivity) obtained with the embodiment of the present invention shown in FIG. 37 are represented in FIG. 44. The contour map indicates that a quasar arrangement favorably reduces the CD variation due to aberrations. However, FIG. 44 also shows that there is a high aberration sensitivity (6-8 nm variation) for poles arranged at exactly +/-45° relative to the horizontal axis of the illuminator. Sensitivity drops (0-2 nm) for source points that are outside the +/-45° position. Aberration sensitivity can be reduced by enlarging poles to dilute the unfavorable on-axis sensitivity. However, a reduction in process window is expected. The contour map in FIG. 44 also suggests that a quasar illuminations having poles larger (0.85/0.50Q45°) (identified as "(a)" in FIG. 44) than those initially selected in FIG. 43 (0.80/0.50Q30°) (identified as "(b)" in FIG. 44) may give better results (as it encompasses a larger area where CD variation is zero).

Page 48, please amend paragraph 241 as follows:

[00241] This assumption is corroborated in FIG. 45, which represents the CD variation of the double line structure as a function of wavefront aberration (in RMS) for

different illumination arrangements. This figure clearly indicates that aberration sensitivity is notably reduced by using a 0.85/0.50 quasar 45° illumination arrangement. For this illumination configuration, CD variation lower than 5 nm can still be obtained even with lens aberrations of up to 60 milliwaves.

Page 49, please amend paragraph 242 as follows:

[00242] FIG. 46 illustrates the variation of the Exposure Latitude as a function of depth of focus for the illumination arrangements used in FIG. 44 (illumination (a) 0.85/0.50Q45° and (b) 0.80/0.50Q30°) and for an on-axis 0.25 sigma illumination (identified as "(c)" in FIG. 46). In each illumination arrangement of FIG. 46(a)-(c), the sigma range along the X-axis and Y-axis is from -1 to +1. The 0.25 sigma illumination (c) is used in combination with an alternating phase shift mask (alt-PSM). The illuminations (a) and (b) are used in combination with a chromeless phase lithography (CPL) mask. As can be seen in this graph, an illumination arrangement having larger poles (0.85/0.50 quasar 45°) may still give a favorable process window. This arrangement represents a good compromise because it favorably reduces CD variation due to aberrations while still maintaining a good process window. Furthermore, a CPL mask gives improved process window.

Page 52, please amend paragraph 256 as follows:

[00256] This approach was successfully pursued to select an illumination arrangement that provides similar results to those obtained with the anti-scatterring bars in FIG. 48. FIG. 48 shows a pattern of 75 nm trenches arranged on a 6% attenuated phase shift mask (6% att-PSM). The pattern includes a 50nm anti-scattering bar on each side of the trenches. The pitch between the anti-scattering bars (on each side of the trenches) is 150nm. As explained above, optimization of the conditions of illumination was first done by selecting the best illumination arrangement using the responses calculated with mask assist features. Selection of the best arrangement was performed with the max DOF and max EL responses. For reference, the variation of these two responses as a function of source point position is represented in FIGS. 49a and 49b. In this trial, the reticle used is a 6% attenuated phase shift mask, the radiation has a 193 nm wavelength and the exposure is done with a 0.93 numerical aperture. A 15 nm positive bias is applied on the mask and the trenches have a 90 nm size on the mask.

Page 52, please amend paragraph 257 as follows:

[00257] As can be seen in FIGS. 49a and 49b, a very wide CQuad or quasar arrangement may be desirable to obtain the best condition of illumination. Results for these types of illumination arrangement in terms of Exposure Latitude are represented in FIG. 50. <u>The pattern is the same as that of FIG. 48 (i.e., 75nm trenches with 50nm side bar per side (1SB/side)).</u> This graph shows the variation of EL as a function of depth of focus for various lengths and sizes of CQuad poles (the length being expressed in arc degree) and for various Anti-Scatterring Bar pitches <u>(varying from 150nm to 180nm)</u>. This graph shows that the best illumination arrangement and the best lithographic process may be attained with ASB disposed in a 160nm pitch and exposed with 22.5 ° CQuad poles. In this trial, a 10 nm and 20 nm positive bias, corresponding to a size of the trench of 85 nm and 95 nm respectively, is applied on the mask.

Page 53, please amend paragraph 258 as follows:

[00258] After finding the best illumination and ASB arrangement, the optimization of the condition of illumination according to an embodiment of the invention shown in FIG. 47 proceeds by calculating the same responses without mask assist features. These results are illustrated in FIGS. 51a and 51b, which represent the variation of these responses as a function of source point location. <u>Calculations are performed with a 6% attenuated phase shift mask (6% att-PSM). A 6% att-PSM generally requires small sigma on-axis pole for dose latitude.</u> Calculation of the separate responses for individual source points and determination of the contour map may be done with the embodiments of the present invention represented, for example, in FIGS. 13 and 18. As can be seen in these figures, the DOF response suggests that a CQuad illumination may be desirable to obtain a good process window. By contrast, the EL response indicates that a small sigma illumination may be best for this lithographic problem. It is therefore expected that a small sigma illumination combined with a wide CQuad illumination would constitute the best illumination arrangement to obtain a large process window.

Page 53, please amend paragraph 260 as follows:

[00260] Using isofocal compensation analysis, it is concluded that one can match at least the results obtained with mask assist features by selecting a 35°CQuad illumination with a 0.1σ illumination. As can be seen in FIG. 52, the CD variation of the trench with this illumination arrangement is relatively stable over a predetermined range of focus. For

reference, the cross section of the resulting beam intensity at the pupil plane of the illuminator is represented in this figure (identified by "(a)").

Page 54, please amend paragraph 262 as follows:

[00262] Referring now to FIG. 53, this graph shows the variation of exposure latitude as a function of depth of focus for the best lithographic process determined with mask assist ~~feature~~ features (same pattern as in FIG. 48) and for an alternative process that does not use assist features but which has been developed to give very good results (same pattern as in FIG. 48 without assist features). As can be seen in this graph, the lithographic process developed without mask assist features gives better results than the process developed with mask assist features. This results show that it is possible to replicate the positive effects obtained with mask assist features by selecting an appropriate illumination arrangement in accordance with the method of the present invention shown, for example, in FIGS 13 and 18. It is therefore concluded that by selecting an appropriate illuminator arrangement with the embodiment of the present invention shown in FIG. 47, one can quickly develop a lithographic process that gives good results without using mask assist features. With the embodiment of the invention shown in FIG. 47, the "assist features" are applied in the illuminator and the need of complex and expensive reticles to print sub 150 nm patterns may be obviated.

Page 54, please amend paragraph 263 as follows:

[00263] It should be noted that by using a "simple mask / complex illuminator" approach as shown in FIG. 47, it is possible to reduce the pattern bias on the mask and, therefore, to increase the depth of focus of the lithographic process. Thus, as there are no assist features present on the mask, there is no risk of opening them by using high exposure energies. It is therefore now possible to use high doses with low bias to improve the process window. To illustrate this principle, reference is made to FIG. 54. This graph shows the variation of the exposure latitude as a function of depth of focus for various biases. Calculations are done with 75 nm trenches, a 6% att-PSM, a 193 nm radiation wavelength and a 0.93 numerical aperture. The pattern of FIG. 48 without assist features (identified as "(a)") and the illumination arrangement (identified as "(b)") are also shown. As can be seen in this graph, it is possible to increase the depth of focus with a -5nm bias (corresponding to a 70 nm trench on mask).

Page 57, please amend paragraph 274 as follows:

[00274] The method of optimization according to the embodiment of FIG. 55 was successfully applied to select the best illumination arrangement for the lithographic problem shown in FIG. 56. This problem corresponds to a pattern of 50 nm twin line structures <u>(identified as "TL" in FIG. 56)</u> printed with a CPL mask. As can be seen in FIG. 57, calculation of the DOF@8%EL as a function of source point location, according to the embodiment of the invention shown in FIG. 16, indicates that a small quasar illumination may be desirable to print for this specific lithographic pattern. <u>Calculations were performed with a 0.82 numerical aperture, a 157 nm radiation wavelength and a resist simulation model. FIG. 57 shows that the "best choice" for illumination based on a process window metric is a 0.64/0.42Quasar30° illumination arrangement. This illumination arrangement corresponds to an off-axis quadrupole illumination arrangement that includes poles arranged at +/- 45° relative to the horizontal axis of the illuminator. Each pole has a 30° opening angle, a 0.42 inner radius and a 0.64 outer radius. As also shown in FIG. 57, smaller poles centered at about the same location are expected to give better process window.</u>

Page 57, please amend paragraph 275 as follows:

[00275] Referring now to FIG. 58, this contour map illustrates the total CD variation, determined in accordance with the embodiment of the invention shown in FIG. 55, as a function of source point location. This graph suggests that a quasar illumination with large poles (or at least larger than those determined in FIG. 57) may be desirable to lower CD variation <u>and to improve the CD uniformity (CDU). As can be seen in FIG. 58, the lowest CD variation is obtained with source points that are slightly off the 45° diagonal</u>.

Page 58, please amend paragraph 276 as follows:

[00276] A comparison of CD variation for different illumination arrangements and for different parameters is shown in FIG. 59. Calculation of the CD variation for each of these arrangements is done with the embodiment of the present invention illustrated in FIG. 55. In FIG. 59, the CDU values were calculated using the actual illuminators <u>(A-E)</u> depicted. <u>The sigma range along the X-axis and Y-axis of the illumination arrangements shown in FIG. 59 is from -1 to +1.</u> However, the CD value for each arrangement may also be determined by averaging the CD values of each point contained within the illumination spots (similarly to the embodiment of the invention shown in FIG. 18)<u>.</u> As can be seen in this graph, the quasar arrangements with poles larger than those determined in FIG. 57 lower the CD variation. <u>The</u>

best conditions are obtained for the following illumination arrangements: 0.64/0.42Q45° and 0.64/0.42Q60°. The process window is expected to increase when the size of the off-axis poles decreases. More importantly, this graph shows that selecting an illuminator based on the process window alone may not be sufficient to reduce CD variation. It is concluded, therefore, that the best CDU approach defined in the embodiment of the invention of FIG. 55 may be a useful tool to optimize the conditions of illumination for a given lithographic problem.